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Techno-economic and life-cycle assessments of biorefineries based on palm empty fruit bunches in Brazil

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ABSTRACT

Lignocellulosic material is one of the most promising feedstock frequently investigated for the biochemicals and biofuels industries. Palm empty fruit bunches (EFB) are the abundant lignocellulosic residues from the palm oil/biodiesel industry, which require special disposal and utilisation. Therefore, the valorisation of EFB as a multi-product bio-refinery feedstock promises to be economically and environmentally attractive. However, it requires further investigation and feasibility assessment. This study conducts techno-economic and life-cycle assessments in Brazil of two EFB-based biorefinery scenarios producing fuel ethanol, heat and power, and C5 syrup (as feed for cattle). In terms of environmental impact, both scenarios show a significant reduction in climate change and fossil fuel depletion. Nevertheless, the economic prospects of the biorefinery scenarios and their benefits for toxicity and eutrophication are limited under the considered conditions.

1. Introduction

Palm oil has garnered huge attention worldwide in recent years. Its worldwide production increased from 52.6 million tons (Mt) in 2011 to 61.7 Mt in 2015 (USDA, 2016). This is expected to continue to grow, mainly due to the expansion plans of Indonesia and Malaysia, the two largest palm oil producers (Prokurat, 2013). The increased interest in palm oil is based on its broad range of use in the food industry, low production cost, the growing production of palm-based biodiesel, and the socio-economic benefits of palm oil production in rural areas (Gilbert, 2012). However, many authors report that the expansion of palm oil can cause damaging effects for the environment (Hansen et al., 2015), including deforestation and reduction of biodiversity (Fitzherbert et al., 2008), while palm based biodiesel provides only negligible benefits, or may even have counterproductive effects, for the reduction of greenhouse gases when deforestation occurs (Hansen et al., 2014). Yet, such perceptions of the sustainability of palm oil production have not curbed the rapid growth of the industry.

The rapid development of the industry has increased the availability of lignocellulosic residues resulting from the palm oil extraction stage. Such residues are mainly from the empty fruit bunches (EFB) that are the remaining parts from the fresh fruit bunch (FFB) stripping. The current world production of EFB amounts to 83 Mt per year (Mt/y). In the palm oil and biodiesel production industries, EFB is often considered a waste product that requires proper utilisation (incineration) and involves disposal costs. The valorisation of EFB becomes a big challenge for the producers of palm oil/biodiesel and a sustainable solution could significantly improve the economic performance of palm oil/biodiesel projects.

The valorisation of EFB is being investigated in several ways. The first method is to use EFB as a mulch or fertiliser at palm plantations or other agricultural fields (De Souza et al., 2010). As EFB is a rich source of carbon and valuable minerals, it could improve the fertility and health of the soil (Gutiérrez et al., 2009). In addition, EFB mulch helps to conserve moisture and reduce weed growth. However, this approach has several drawbacks including a restricted application area and the hard decomposition of the tough EFB material. Another interesting method is to use EFB as a fuel for heat and electricity generation (Hosseini and Wahid, 2014). This process includes drying, shredding, and, if required, pressing the EFB into convenient briquettes that are easy to distribute and burn. However, the economics of such a process is still doubtful, mainly because of EFB's large moisture content (above 50%) (Yusoff, 2006).

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Thermochemical conversion of EFB to syngas or hydrogen represents another promising option for the exploitation of residual biomass for energy purposes (Mohammed et al., 2011). This approach leads to interesting economic and environmental prospects, although further research and scale testing are required (Lahijani and Zainal, 2011).

One promising and sustainable alternative is the biochemical conversion of EFB into fuel and high-value added products. This method is in line with the world trend towards partial replacement of fossil-based fuels and chemicals with 'green' equivalents; for example, the increase in world production of fuel ethanol from 50 to 93 billion L/y between 2007 and 2014 (AFDC, 2016). In addition, lignocellulosic material is a very probable resource base for bioethanol production (Bhutto et al., 2015). The biofuels produced from residues, like EFB, are known as second generation biofuels (2G) (Naik et al., 2010). One of the main advantages of 2G ethanol is its sustainable production from abundant feedstock, which has limited competition with food production (Karlsson et al., 2014). The utilisation of EFB through bioethanol production is particularly interesting and potentially valuable in Brazil, the second biggest producer and consumer of fuel ethanol, with a well-developed fuel ethanol market and infrastructure (AFDC, 2016). However, despite recent achievements and such prospects, the production cost of 2G bioethanol remains relatively high. The economic and environmental viability of the 2G process could be improved through the use of a biorefinery plant, namely, the co-production of several bio-based goods (Kajaste, 2014). Many studies have demonstrated the benefits of the integration of 1G-2G ethanol production with heat and electricity co-generation in the context of Brazil (Dias et al., 2011). Recent studies investigated the co-production of 1G-2G plants with other products such as sugar, C molasses, and C5 syrup for animal feed. (Gnansounou et al., 2015). However, these studies focus mainly on sugarcane-based biorefineries, utilising bagasse and green harvesting residues, while there is scant research on the concept of a palm-based biorefinery consuming EFB as lignocellulosic feedstock. Moncada et al. (2014) and Quintero et al. (2013) assessed the techno-economic prospects of bioethanol production from EFB and identified the high potential of such production in the Colombian context. Ali et al. (2015) proposed a general concept of an integrated palm oil biorefinery with the value-added of the biomass and zero emission system. Delivand and Gnansounou (2013) investigated the potential of EFB as a feedstock for 2G ethanol in the Brazil context, however, without a techno-economic assessment and feasibility study.

This study aims to evaluate the economic feasibility and environmental impacts of the valorisation of EFB as a biochemical pathway in the Brazil context. The first question to be answered is whether the EFB biochemical valorisation is a feasible option for the palm oil industry in Brazil, and what recommendations can be provided for an EFB-based biorefinery. The second question is about the environmental benefits of the conversion of EFB into bio products and what scenarios would be most favourable. Bearing in mind the Brazilian context and preference for industry partners, this study focuses on three realistic products: 2G bioethanol as car fuel, C5 syrup as cattle feed, and electricity. The production of these selected products is considered in two EFB-based biorefinery scenarios: (1) production of 2G bioethanol, power and heat, and animal feed (C5 syrup); (2) production of 2G bioethanol and power and heat. The economic feasibility and environmental performance of the scenarios are evaluated according to techno-economic assessment and life-cycle assessment (LCA) principles. The results of the assessments of both scenarios are compared along with those from conventional reference systems to better understand the benefits of the bio-based alternatives.

2. Case study

The case study is located in the state of Pará, in the northern part of Brazil, where the lower Amazon river flows to the sea. Pará has total area of about 1,248,000 km^2 and population of about 7,800,000 people, equating to a low population density of around 6.2 inhabitants per km^2. The climate is equatorial, with average temperatures near 26 °C and annual rainfall around 1500 mm. Such climate conditions are very favourable for growing palm trees. Around 99% of the palm oil farms in Brazil are located in Pará. The Amazon represents over half of the world's remaining rainforests and includes the largest and most species-rich tracts of tropical rainforest. However, Pará suffers from illegal deforestation and land occupation, primarily from cattle ranching and soya farming. At present, about 18 M ha of land are pasture. Rather than harmful land expansion in the forest from palm oil farms, the conversion of degraded pasture/grassland into palm tree plantations could bring benefits that could be part of Brazil's reforestation initiatives (Brazil Government News, 2016).

In this study, the total capacity of a palm oil extraction plant is assumed to be 2,000,000 FFB t/y (wet basis - w.b.), providing approximately 420,000 EFB t/y (w.b.) waste with a 62% moisture content. Such a scale corresponds to a total area of about 110,000 ha of palm plantations, with an average annual yield of 18 FFB t/ha. The agricultural and logistic details of the case study can be found in Delivand and Gnansounou (2013). The palm oil cultivation land is assumed to be recently converted from pasture land. The lifetime of the project is 25 y and the number of operating d/y is 300.

Bearing in mind the study goals, the selection of possible biorefinery products was based on an analysis of Brazil's economic needs, industrial partner preferences (Biopalma, 2016), and existing literature. Specifically, the market prospects of ethanol, C5 syrup, and electricity seem to be attractive for several reasons. Blends of gasoline and anhydrous ethanol are widely used as transport fuel in Brazil. The C5 syrup, rich in soluble sugars, is an attractive feedstock for cattle feed in a developed livestock industry. The biorefinery practice of producing and selling electricity has been successfully tested in many Brazilian sugar mills where bagasse is burnt. Regarding environmental prospects, the 2G biofuel and products based on lignocellulosic biomass are more environmentally friendly than their 1G and fossil based counterparts (Cherubini et al., 2009). As previously mentioned, two scenarios are considered in this study: the EFB 'feed-fuel' (EFB FF) scenario, which produces fuel ethanol and syrup from C5 sugars as a cattle feed supplement; and the EFB 'only fuel' (EFB OF) scenario, which produces only ethanol fuel as the main product. Both scenarios produce electricity and steam, consumed mainly to satisfy the biorefinery heat and power demands. However, surplus electricity, if available, could be sold to the local market, providing additional revenue.

3. Materials and methods

3.1. Process design

The process design for the two biorefinery scenarios – EFB OF and EFB FF – is based on the strategy developed by the National Renewable Energy Laboratory (NREL) to produce ethanol from corn stover and experimentally tested at a pilot plant (Humbird et al., 2011). Changing from corn stover to EFB feedstock in the NREL model may lead to relevant discrepancies in the ethanol yield, utilities consumption, or inputs required for running the plant. The major carbohydrates of both EFB and corn stover are the same but differ in their weight percentage. The detailed study published by NREL allows other researchers to reproduce the simulation process

component by component. In addition, the electricity demands of the equipment in the NREL model depend only on the scale of the mass flow rates of the process streams. Thus, the NREL process design is assumed to be suitable for studying the EFB process. The technology employed by the NREL in 2011 is used here to process EFB assuming the same operating conditions as reported by the NREL (Humbird et al., 2011). The NREL design is adapted by modifying the feedstock composition and plant capacity for the EFB scenarios. Other changes in the model (conversion fractions of some reactions, inputs removal, modification of units, and distribution of utilities) are discussed further.

The composition analysis of raw EFB was experimentally conducted at the Bioenergy and Energy Planning Research Group's (BPE) laboratory, as shown in Table 1 (Raman and Gnansounou, 2014). The capacity of the residue processing plant is assumed to meet the assumption in Section 2 around EFB, but on a dry basis. Consequently, 532 EFB t/d (dry basis - d.b.) enter the lignocellulosic processing plant (2G plant) to produce ethanol and co-products. A cogeneration system annexed to the 2G plant is included in the design of the scenarios to provide heat and power. The simulations of the biorefinery scenarios were performed using Aspen Plus V8.8. The global base method used was NRTL (Non-Random Two Liquid model). In the pre-treatment, a flash block used the NRTL-HOC local property method. This method is advisable to model the association of acetic acid to form dimmers in the vapour phase (Humbird et al., 2011).

The NREL's 2011 model (Humbird et al., 2011) presents data for the electricity consumed by corn stover pre-processing in a specific format (size distribution, moisture, and bulk density) in a feedstock-supply area. In the simulation model, the electricity required in the feed handling area is adapted from the NREL feed rate (2000 t/d d.b.) for the present case (532 t/d d.b.). In addition to the EFB preparation area, the simulated scenarios include the following areas: pre-treatment (30% solids loading), saccharification (20% solids loading), fermentation, distillation, wastewater treatment (WWT), and combined heat and power cogeneration (CHP). An extra unit for C5 syrup production was added after pre-treatment in the EFB FF scenario.

In the EFB OF scenario, the hemicellulose of EFB was hydrolysed by dilute acid (DA) pre-treatment. DA is one of the pre-treatment methods providing a higher recovery of soluble pentoses (C5) while preparing cellulose for an easier enzymatic hydrolysis. The EFB biomass is first preheated with high pressure (HP) steam (1.32 MPa). Second, 22.1 mg of sulphuric acid per g of dry EFB are added to catalyse the hydrolysis (Humbird et al., 2011). The reactions were simulated as stoichiometric at 158 °C and saturated conditions producing soluble sugars. The use of acids for the pre-treatment of the biomass, depending on the concentration, may lead to the production of inhibitors since the accumulation of H^+ promotes the degradation of fermentable sugars. Subsequently, the hydrolysate slurry is conditioned for optimal fermentation conditions and inhibitors control. To do this, all the pre-treated slurry is fed into a conditioning reactor with 30% solid content, where an aqueous solution of gas ammonia and water are injected for pH control without a previous solid-liquid separation step. Afterwards, a small amount of sulphuric acid (0.0062 mg H_2SO_4/g EFB d.b.) is added to adjust the pH to the optimal pH fermentation of 4.5. The diluted conditioned slurry (20% solid content) is conveyed to enzymatic hydrolysis.

Table 1
Composition of empty fruit bunches.

Components	Content (wt%)
H_2O	62.0
Extract	3.1
Cellulose	13.0
Galactan	0.1
Xylan	10.0
Arabinan	0.8
Lignin	8.0
Acetate	2.0
Ash	1.0

A liquid hot water (LHW) pre-treatment was chosen in the EFB FF scenario, where the liquid fraction containing soluble (C5) sugars was separated from the solid fraction to produce syrup for animal feed following the Integrated Biomass Utilisation Systems (IBUS) concept (Larsen et al., 2008). LHW is a chemical free process that hydrolyses hemicellulose by steam and prevents the forming of inhibiting compounds. LHW is less efficient than DA but offers more environmental advantages (Gnansounou et al., 2015). In addition, the assumed relatively mild conditions of the LHW technique (Larsen et al., 2008) enable it to avoid inhibitor production. For this reason, the liquid stream after the LHW pre-treatment is suitable for C5 syrup production and does not require a further detoxification step. The FF LHW pre-treatment model is a modification of the NREL model based on general hydrothermal pre-treatment (Carvalheiro et al., 2009). In this case, the reactions take place at more severe conditions (180 °C). The hydrolysate is separated into liquid and solid fractions by a Pneumapress® pressure filter. Of the cellulose present in EFB, 90% is recovered in the solid fraction, which includes lignin and most of the non-reacted hemicellulose. The liquid fraction contains soluble sugars, and some of the cellulose and hemicellulose not recovered in the solid fraction. The liquid fraction is concentrated in a three-effect evaporator to achieve dry matter content of 65% in the syrup, comprised of 54.1% of C5 sugar and 39.5% of C6 sugar. In conclusion, the LHW pre-treatment is preferred in the EFB FF scenario since the liquid fraction obtained is free of toxic chemicals and fully suitable for cattle feed production.

After pre-treatment the treated stream is ready for the separate hydrolysis and fermentation (SHF) process. To decrease their viscosity and to facilitate the operation in the saccharification reactor, the solid fraction (EFB FF) and all of the conditioned slurry (EFB OF) are first liquefied by adding the cellulase enzyme. The enzyme loading is 19.92 mg cellulase/g cellulose in the hydrolysate, near the optimal loading value required to achieve a 90% conversion to glucose (Humbird et al., 2010). The saccharification process is carried out in a continuous reactor followed by a batch one at 48 °C and 0.1 MPa. After 3.5 days, 90% of the cellulose is converted into glucose and the saccharified slurry is ready for fermentation.

At this stage, 10% of the saccharified slurry is fed into the seed fermenter reactor to produce the seed culture, while the remaining is inoculated for fermentation. The recombinant *Zymomonas mobilis* bacterium was chosen for fermentation since this microorganism is able to simultaneously co-ferment glucose and C5 sugars to ethanol (Zhang et al., 1995). Fermentation takes place in a bioreactor at 32 °C and 0.1 MPa. The process duration is 36 h, in which the batch operation requires 24 h and the turnaround time 12 h. Following the NREL outcomes, 95% of glucose and 85% of xylose fractional conversions to ethanol were assumed; 3% of the sugars available for fermentation was modelled as a loss due to contamination. The concentration of ethanol in the fermentation broth was about a 7% wt. This condition is appropriate for beer distillation and subsequent purification.

Beer distillation was modelled using a RadFrac block available in Aspen Plus for simulating a multistage distillation column. The column is constructed with 21 trays, a partial vapour condenser, and a kettle reboiler. The fermentation broth enters above the seventh tray of the ethanol, and 99% leaves the column as a vapour-

side drawn on the eighth tray. The conditions at the top of the column are set to 0.20 MPa and 60 °C, and the pressure drops 0.02 MPa throughout the entire column. The solids and 0.05% of the ethanol stay at the bottom of the column. The evaporated ethanol-water mixture is fed into the 16th tray of the RadFrac column with 35 stages (0.16 MPa), a partial-vapour condenser, and a kettle reboiler. Of the ethanol, 92.5% is released in a vapour state from the top of column. Saturated water leaving through the bottom is recycled for pre-treatment. The ethanol stream is purified to 99.5% by adsorption. Lignin contained in the beer distillation bottom is fractionated by filtration. Of the non-fermentable solubles, 50% fall in a liquid stream conveyed to a wastewater treatment area. The other 50% are burnt in the cogeneration area with the solids.

The WWT area is simulated as in the NREL's 2011 model (Humbird et al., 2011). This area produces clean water to be recycled within the plant and generates fuels, including sludge and biogas, to be combusted in the boiler at CHP. The lignin cake and the dirty air produced in the distillation process are also funnelled into the combustor. The combustion reactions were simulated as stoichiometric at 0.098 MPa and 870 °C. The heat released from the combustor is employed for generation of superheated steam at 6.08 MPa and 454 °C. The superheated steam passes through a multistage turbine operating at 1.32 MPa (a portion of high pressure steam at 266 °C is pulled apart for pre-treatment), 0.963 MPa (low pressure steam at 233 °C is destined to satisfy the heat required by other units at the plant), and 0.01 MPa (where the non-used low pressure steam is condensed) to generate electricity. In this way, electricity and heat are cogenerated at the plant using its own residue leading to cost reduction by avoiding waste disposal. Additional revenue may also be generated by selling any excess electricity produced after satisfying the plant's demand.

3.2. Techno-economic assessments

Techno-economic assessment was performed via a value-based approach proposed by Gnansounou and Dauriat (2010). This method is based on the calculation of the values of all the process streams attributed to the main project's economic parameters such as the products' operational costs, capital investments, and market prices. One of the main advantages of this approach is that it allows for the comparison of different projects and scenarios that compete for the same resource base. Taking such competition into consideration, the value-based approach focuses on the assessment and comparison of the EFB values in the scenarios in this study.

The method consists of a comparison between the maximum purchasing price (MPP) of feedstock and its minimum selling price (MSP). The MPP is the maximum price that the biorefinery can afford to pay for feedstock to be economically efficient. The MSP is the lowest possible price that could satisfy a supplier of feedstock. The difference between both prices gives the prospective economic performance (PEP) of the biorefinery, as shown in (Eq. (1)).

$$PEP = MPP - MSP; \tag{1}$$

The biorefinery project with the greater PEP value has a better economic performance than the project with a smaller one. The MPP is calculated according to the value-based approach and depends on different techno-economic parameters such as capital and operation costs, prices of issued products, inflation rate, and lifetime of the project.

The calculation process begins with the decomposition of the complex process into process stages and with the assessment of the values of the inputs and outputs of the process streams for each stage in terms of contribution to the market values of the final products and the capital and operation costs required in those stages (Fig. 1). The stream value calculations are based on the idea that the sum of the values of the inputs equal the sum of the values of the outputs. In practice, it means that if calculations start at the stage that issues the market products and moves to the beginning of the production line that receives the feedstock, the value of the feedstock (MPP) will include the sum of the values of all processes minus all conversion costs associated with goods production, namely, capital investments, fixed operation costs, and variable operational costs. The capital annuity, operation costs, and value of utilities, that is, heat, water, and electricity, are considered as inputs at each stage. The value of the utilities is considered as production cost that includes only capital investment and operational costs attributed to the utility production stages and not the value of the process streams (e.g. lignin and biogas) entering the utility production stages. This allows for the accurate allocation of the capital investment and operational costs of the cogeneration plant, WWT, and utility process stages among the products of the biorefinery by given values of consumed heat, electricity, and process water. The calculation begins at the cogeneration stage and is finalised at the handling stage, when the value of EFB is calculated, namely, the MSP of the EFB. The values obtained from the intermediate streams are used to calculate the stream allocation factors at the stages that have more than one output stream. Further details of the methodology can be found in Gnansounou et al. (2015).

The production cost of the goods was calculated to analyse the results of the overall economic assessment and compare the evaluated scenarios. The production cost calculation is a reverse procedure to the aforementioned calculation of the values of the process streams. The calculation begins at the handling stage and continues to the stage when market products are issued. If a stage has more than one output stream, the allocation factors from the previous step are used to allocate costs between the stage outputs. The PEP in terms of \$/t of feedstock can be estimated as the sum of the difference between the market price of the good and its production cost multiplied by the good's yield, as shown in Eq. (2).

$$PEP = \sum_i (X_i - Y_i)Z_i; \tag{2}$$

where X_i is the market price of product i, Y_i is the calculated production cost of product i, and Z_i is the yield of product i per feedstock.

Calculations of capital investments and variable and fixed operating costs are based on the NREL report (Humbird et al., 2011). This report provides essential information on prices and equipment, facilities, and chemical costs, among others, for 2G ethanol production from corn stover in the US context. The costs of facilities and equipment at a scale other than that presented in the NREL report are calculated according to an exponential scaling expression (Eq. (3)), with scaling factor equal to 0.6 (Dias et al., 2012).

$$NewCost = OriginalCost\left(\frac{NewSize}{OriginalSize}\right)^n; \tag{3}$$

Costs and prices were recalculated to a reference year by using the Chemical Engineering Plant Cost Index (Humbird et al., 2011). The operation of the project was expected to begin in 2020; however, the reference year used was 2010. The main economic parameters of the project, including products, feedstock prices, and discount rate, are summarised in Table 2.

Taking into account the possible fluctuation of ethanol, C5 syrup, and electricity prices in Brazil, the sensitivity of economic efficiency to product price changes was investigated. The range for ethanol prices was considered from \$600 to \$1400 per metric t of fuel ethanol, the range for C5 syrup from \$155 to \$455 per t, and

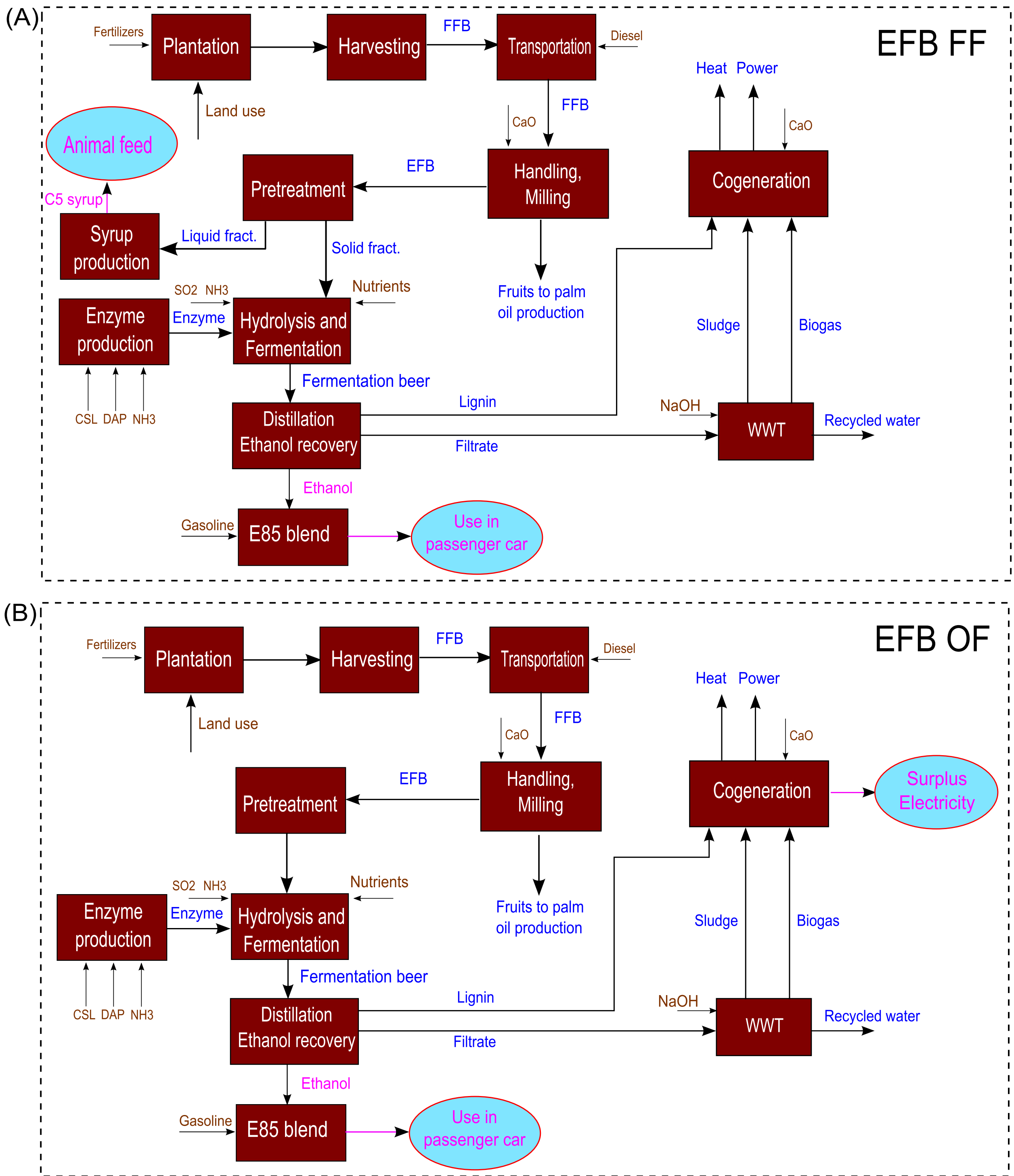

Fig. 1. System boundaries of EFB FF (A) and EFB OF (B) scenarios.

electricity prices from \$0.04 to \$0.14 per kWh. The results of the techno-economic assessments and sensitivity analysis for the two EFB-based biorefinery scenarios (EFB OF and EFB FF) are presented in Section 4.2.

3.3. Environmental assessment

3.3.1. Goal and scope definition

The environmental assessments of the selected scenarios were performed according to LCA principles. This methodology assesses environmental impacts associated with the entire life cycle of a product, from cradle to grave. The LCA methodology used here is based on the International Organization for Standardization (ISO) principles (ISO, 2006a; ISO, 2006b) and includes four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation.

This first step in LCA states the main goal and defines the basic assumptions and key parameters of the assessment. Specifically,

Table 2
Prices and project parameters used in the economic analysis.

Project lifetime, years	25
Reference year	2010
Discount rate, %	10
EFB price (MSP), \$/t (w.b.)[a]	12
Fruits price, \$/t (w.b.)[b]	129
Ethanol price, \$/t[c]	760
Syrup C5 price, \$/t[d]	155
Electricity price, \$/kWh[c]	0.08

[a] Montafia and Gnansounou (2017).
[b] Price is based on the price of FFB that is 14.25% (Brandao and Schoneveld, 2015) of the market price of traded crude palm oil (\$716/t) (FOSFA, 2017).
[c] Dias et al. (2012).
[d] CEPEA (2015) (price of C5 syrup adjusted to sugar price).

functional units, system boundaries, the allocation method, and reference systems are identified at this stage. The main goal of the LCA in this study is to assess the environmental impact caused by running the selected scenarios of the EFB-based biorefinery and compare these results with results from relevant reference systems. Accordingly, the functional unit of the assessment is 1 t of EFB for both cradle-to-gate (CtG) LCA and well-to-wheel (WtW) LCA in the case of ethanol LCA. This functional unit allows for the comparison of multi-product scenarios based on the same feedstock. The system boundaries for scenario EFB FF are presented in Fig. 1(A) and for EFB OF in Fig. 1(B). These show that the system boundaries are comprised of the agriculture and transportation stages of EFB production, logistics, the biochemical conversion of EFB into several products, and, finally, the use of the selected product in specific services. Five environmental impact categories are selected for the analysis: climate change (kg of CO_2 eq.), fossil fuel depletion (kg oil eq.), human toxicity (in kg 1,4-DB eq.), freshwater eutrophication (in kg P eq.), and freshwater ecotoxicity (in kg 1,4-DB eq.). The climate change and fossil fuel depletion impacts are included in the assessments since the mitigation of impacts on global warming and the use of fossil resources are relevant environmental challenges in our time. The human toxicity impact has also been analysed, as the products of the system are intended for daily use. Finally, since biodiversity in Brazil is a big concern, the impacts on the aquatic ecosystems, that is, freshwater eutrophication and freshwater ecotoxicity, were included in the analysis.

Each biorefinery scheme was compared to a relevant reference system (RS). It is worth mentioning that in the LCA methodology, the definition of the reference system (RS) plays a crucial role and directly influences the results. In this study, each product produced through the biorefinery is first converted to its correspondent service, and then compared to a similar service using a conventional product. The current biorefinery schemes can produce up to three products: fuel ethanol, C5 syrup, and electricity. As a result, the three services included in the analysis are: car operation (fuel ethanol vs. gasoline), cattle feed supplement (C5 syrup vs. C5 molasses), and grid electricity (from CHP vs. Brazil mix). Fig. 2 shows the simplified definitions of the RSs compared with the systems under EFB FF (A) and EFB OF (B) scenarios.

The comparison of fuel ethanol and gasoline requires the calculation of fuel efficiency of ethanol in a selected fuel blend. Here, an E85 blend with 85% ethanol to 15% gasoline (v/v) is assumed. The calculation of the biofuel efficiency is based on the methodology proposed by Gnansounou et al. (2009).

$$FE_{biofuel} = \frac{BF_{biofuel}FE_{fuelblend}}{1-\left(1-BF_{biofuel}\right)\frac{FE_{fuelblend}}{FE_{fossilfuel}}}; \tag{4}$$

where $BF_{biofuel}$ is the biofuel blend factor, that is, 0.85 for chosen blend E85; $FE_{fuelblend}$, $FE_{fossilfuel}$, and $FE_{biofuel}$ are the fuel efficiencies, L/km, of the fuel blend, the fossil fuel (gasoline), and the biofuel. $FE_{fossilfuel}$ for gasoline (EURO4) in Brazil is 7.48 L/100 km (Delivand and Gnansounou, 2013); $FE_{fuelblend}$ is around 10.1 L/100 km, according to the data on increased consumption of fuel blends in comparison with consumption of pure gasoline (Gnansounou et al., 2015). Finally, Eq. (4) calculates the efficiency of ethanol in E85, which is equal to 10.76 L/100 km. As a result, it is possible to compare the same travelled distance in a car consuming E85 and a car consuming gasoline (EURO4).

The cattle feed supplement service is employed to evaluate the C5 syrup production in the EFB FF scenario (Fig. 2(A)). This feed supplement is based on its sugar equivalent. The reference service consists of molasses with a sugar content of 73% produced from sugarcane in Brazil. The equalisation between the reference system and the study is achieved by calculating the sugar equivalent based on the sugar content provided by C5 syrup and the molasses reference. Finally, the surplus of electricity from the biorefinery is compared with electricity mix from the Brazilian electrical grid.

Fig. 2 shows the land use presented in the reference system. Emissions caused by a change in the land category constitute an important factor in the environmental analysis of bioenergy systems. In this study, it is assumed that lands where feedstock is produced were initially converted from pasture. The temporary uptake of biogenic carbon in biomaterials and plants (e.g. FFB and palm trees) is not considered as storage; rather, the change in t C/(ha y) in this study is associated only with a change in mineral soil. The effect of land-use changes (LUC) is considered in a 25-y horizon. The greenhouse gases (GHG) emissions associated with LUC are allocated only to the first generation of the plantation use. The LUC emission caused by a change in carbon stock is included in the climate change impact category and evaluated according to IPCC methodology (IPCC, 2006) (Eqs.((5)–(7)).

$$\Delta C_{change} = \Delta C_{\min} = \frac{(SOC_0 - SOC_T)}{T}; \tag{5}$$

$$SOC_T = SOC_o F_{LU} F_{MG} F_I; \tag{6}$$

$$L_{GHG} = \frac{44}{12}\Delta C_{change}; \tag{7}$$

ΔC_{change} is an annual change in the carbon stock of the converted land, t C/(ha y); $\Delta C_{\min}$ is an annual change in the carbon stock in the mineral soil, t C/(ha y); SOC_0 is the soil's organic carbon stock at the beginning of the inventory time period. Here, it is assumed that the previous land use category, right before conversion to the palm plantation, was a moderately degraded pasture with SOC_0 equal to 52 t C/ha for medium active clay soil (IPCC, 2006 -Table 2.3); SOC_T is the soil's organic carbon stock in the last year of the inventory time period, t C/ha; T is the number of y in the inventory time period. F_{LU} is the stock change factor for land-use systems, namely, 1 for long-term perennial tree crops (IPCC, 2006 - Table 5.5). F_{MG} is the stock change factor for the management regime, namely, 1.22 for the tropical wet climate type, and no tillage management regime for cropland (IPCC, 2006 - Table 5.5). F_I is the stock change factor for the input of organic matter, that is, 1 for medium input to the field in this study (IPCC, 2006 - Table 5.5). L_{GHG} is the GHG caused by a change in the carbon stock of the converted land, kg CO_2 eq./y. The LUC is allocated between EFB and palm fruits using the allocation factors from Table 8, the handling stage. Specifically, the allocation factor of EFB is 2.41%, which means that 2.41% of LUC emissions corresponds to EFB and the rest (97.59% of L_{GHG}) corresponds to palm fruits that are not considered in the present biorefinery

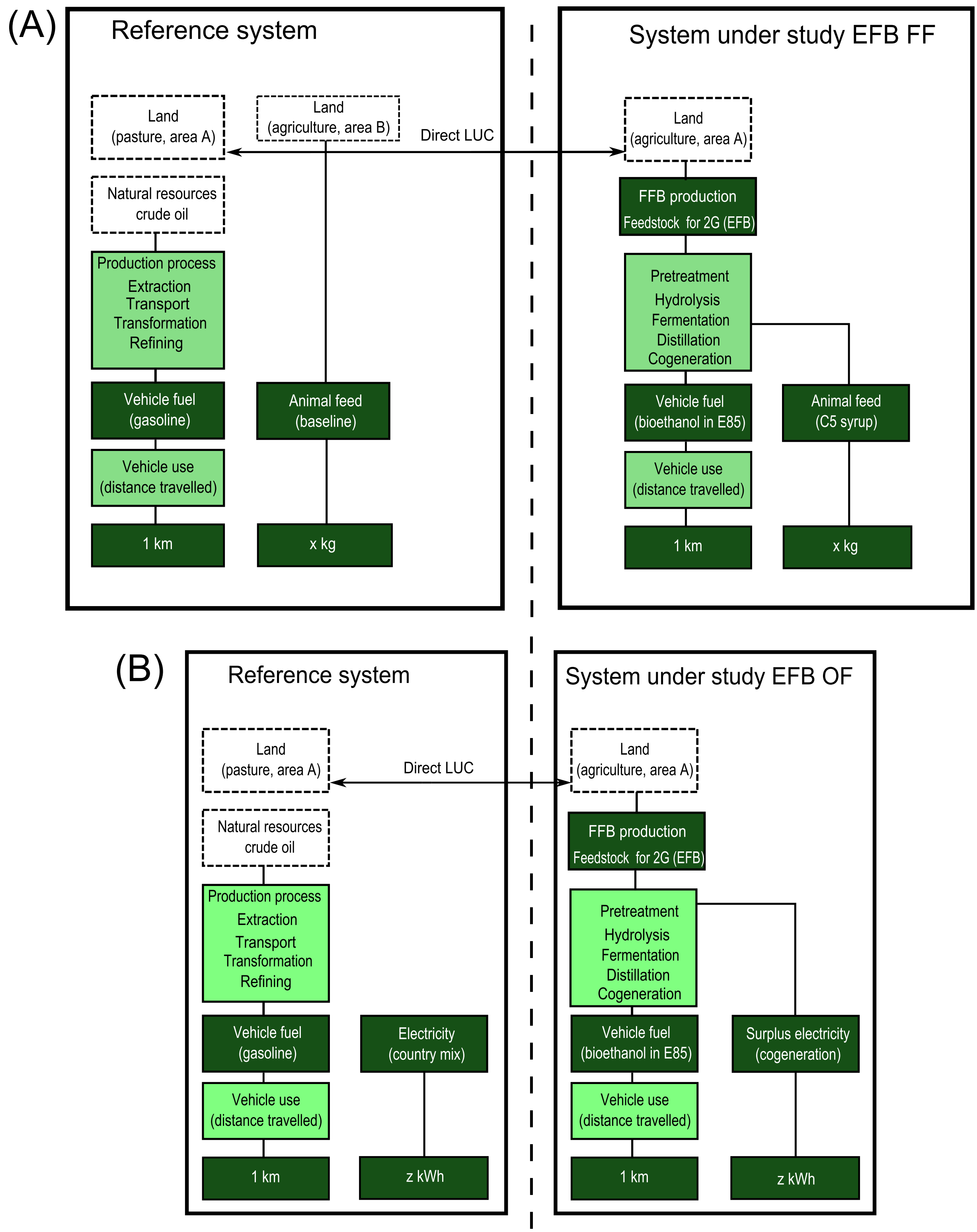

Fig. 2. Reference systems and systems under EFB FF (A) and EFB OF (B) scenarios.

concept. The results are presented in Section 4.3.

To compare the environmental impacts between competitive products and process streams, an economic based allocation is applied throughout the whole assessment of the biorefinery process. Despite the fact that economic allocation has potential limitations arising from the variability of prices and the low correlation between prices and physical flows, it is still suitable to illustrate the properties of complex systems like the multi-product biorefinery (Ardente and Cellura, 2012). In the present study, the economic allocation is performed considering the results of the techno-economic assessment where the values of each intermediate stream and product are identified according to the value-based

methodology (Section 3.2). Allocation between fruits and EFB is based on the market values considered in this study (Table 2). Notably, only positive values of allocated streams lead to nonzero allocation factors.

3.3.2. Inventory analysis, impact assessment, and interpretation

The next step in the analysis is the life cycle inventory (LCI). The LCI captures the accurate quantitative evaluation of all the flows in and out of the product system including raw materials, energy, water, and emissions. In this study, data for the agricultural phase were taken from the Ecoinvent 3.0 database and literature sources (Delivand and Gnansounou, 2013). The inputs and outputs associated with the biorefinery process were from the computer process simulation via the Aspen Plus software v. 8.6 (Section 3.1). The inventory results are used for environmental impact assessment at the next stage. The five chosen environmental impacts (Section 3.3.1) were quantified according to the ReCiPe methodology via the SimaPro v8.0 LCA software. The ReCiPe method is chosen because it integrates and harmonises the midpoint and endpoint approach into a consistent and convenient framework. The impact assessment is completed stage-by-stage starting from the agricultural stage to the utilisation of products in specific services, as depicted by Fig. 1. At each stage with more than one output stream, the associated impact is allocated among these streams according to their allocation factors (Section 3.2).

The final phase of the LCA is interpretation, which is comprised of a careful analysis of the results, followed by conclusions and suggestions. In addition, since the main calculations are based on assumptions and literature data, the uncertainty of the LCA results was assessed through a Monte Carlo simulation in the SimaPro software, assuming the lognormal distribution with standard deviation (SD) of the inputs equalled 2, using a total of 1000 iterations in the analysis (Goedkoop et al., 2013).

4. Results and discussion

4.1. Process design results

Table 3 shows that the EFB OF scenario provides the higher yield of ethanol (et.) (107 kg et./t EFB) production from EFB compared with the EFB FF scenario. This result is explained by the fact that in the EFB OF scenario, all sugars are fermented into ethanol, while in the EFB FF, the soluble sugars are separated after pre-treatment to produce syrup. Table 3 shows that in the EFB OF scenario, the amount of biogas obtained is much higher than that obtained in the EFB FF case. Moreover, the wastewater mass flow in the EFB OF scenario is higher than in the EFB FF one because of the lack of syrup production in the EFB OF case (see Table 3). In addition, the wastewater stream that is fed to the EFB OF digester contains more nutrients (5.81 wt% nutrients) than the equivalent stream in the EFB FF scenario (1.65 wt% nutrients). This difference leads to a higher biogas production in the EFB OF scenario than in the EFB FF one.

Table 3
Mass flow rate of the main streams running the process in EFB OF and EFB FF scenarios.

Stream	Mass Flow rate (t/h)	
	EFB FF	EFB OF
Feedstock (EFB) to plant	58.33	58.33
Chemicals for pre-treatment	0	1
Hydrolysate to SHF process	78.09	113.33
Enzymatic stream	3.76	3.53
Liq. frac. to syrup production	81.3	0
Ferm. broth to distillation	81.04	120.52
Beer from fermentation	3.36	6.26
Waste water to WWT	73.27	106.74
Caustic for WWT	0	0.04
Biogas to Cogeneration (CHP)	0.89	10.12
Sludge to CHP	1.29	5.82
Lignin to CHP	14.54	12.75
Lime for CHP	0	0.01

The availability of surplus electricity provided by the cogeneration area depends on both electricity and heat process requirements in the biorefinery (Tables 4 and 5). The EFB OF scenario uses less energy than the EFB FF one and is self-sufficient, even providing a surplus of electricity (Table 6). In the EFB FF scenario, extra electricity or fuel must be purchased to meet the plant's energy demand. The EFB OF scenario presents a higher value of electricity production (0.66 GJ/t EFB w.b.) and surplus (0.03 GJ/t EFB w.b) without any other fuel source purchases (Fig. 3). These results indicate that the fermentation of all available pre-treated lignocellulosic material and further distillation of products in the EFB OF plant requires a lower energy demand than the evaporation of water in the pre-treated liquid fraction to produce C5 syrup in the EFB FF scenario.

4.2. Techno-economic assessment results

The main outputs of the simulations, economic analysis, investment data, and operational costs are shown in Table 7. The details of variable operation costs, fixed operational costs, and capital investments are presented in supplementary material (Tables A3, A4, and A5). By analysing the results of total capital investments (TCI), variable operation costs (OC), and fixed operation costs (FOC), notably, TCI, OC, and FOC for the EFB OF scenario are higher than in the EFB FF one. This fact is explained by the larger scale of the ethanol production equipment and the more extensive use of chemicals in the case of the 'only fuel' scenario (Table 3). The results indicate that both evaluated scenarios provided negative MPP values for EFB feedstock: −18.07 $/t for EFB OF and −20.38 $/t for EFB FF, which led to negative prospective economic performance in both scenarios. As a result, both biorefinery scenarios are economically inefficient. Primarily, these results can be explained by the high investment cost for 2G ethanol production including the WWT and cogeneration plants (Table A5).

Table 7 shows that the production cost of ethanol is significantly higher ($1038/t) in the case of the EFB OF scenario than the production cost ($849/t) in case of the EFB FF scenario and its considered market price ($760/t, Table 2). The reason for this is that in the case of the EFB OF, almost all the investment and operation costs are attributed to ethanol production, while in the EFB FF scenario, a significant part of the pre-treatment cost is assigned to C5 syrup according to the allocation factors (Table 8). All values of the streams of each process stage used for economic allocation for the EFB FF scenario are presented in Table A6 and for the EFB OF one in Table A8 (supplementary material). The production costs of the streams for EFB FF are in Tables A7 and for EFB OF in Table A9 (supplementary material).

An increase in the 2G EFB biorefinery scale could help improve the economic efficiency of the plant. However, preliminary calculations show that the scale required to make the process economically efficient would be near to 1,400,000 t EFB/y, which corresponds to a total area of 380,000 ha of palm plantation. Today, the project plantations are located in an area of approximately 110,000 ha. An increase in the palm cultivation area of more than three times would most likely be problematic due to the unavailability of suitable land in Pará. The conclusion is that the scaling up of the plant could not be a solution to improve the economic feasibility of the project in the present context.

Table 4
Utilities (electricity, heating, and cooling requirements) in the different sections of the biorefinery.

Sections of the plant	Electricity (GJ/h)		Heating (GJ/h)		Cooling (GJ/h)	
	EFB FF	EFB OF	EFB FF	EFB OF	EFB FF	EFB OF
Pre-treatment	12.1	12.1	28.5	21.4	24.0	16.7
Saccharification and Fermentation	2.4	3.3	0.0	0.0	6.4	26.1
Syrup Production	0.0	0.0	60.2	0.0	0.0	0.0
Distillation and ethanol recovery	1.5	2.2	25.4	41.3	5.3	9.8
WWT	6.0	8.1	0.0	0.0	0.0	7.0
Cogeneration	1.5	1.5	16.4	17.6	0.8	47.9
Other (Feed handling, enzyme production, storage and utilities)	9.8	11.2	0.5	0.4	11.1	10.4

Table 5
Energy converted to heat and electricity at the CHP in GJ/h.

Energy streams	EFB FF	EFB OF
Total electricity produced	22.5	39.9
Surplus	0.0	1.5
Electricity required from external source	10.7	0.0
Total heat produced	154.4	169.0

Fig. 4 shows the dependence of the PEP of biorefineries on the fluctuation of ethanol, electricity, and C5 syrup prices (see Fig. 4(A), (B), and (C)). It can be concluded that the biorefineries could be profitable based on the wide range of ethanol and C5 syrup prices; however, the fluctuation of the electricity prices could not achieve relevant profitability improvement in a realistic price range. Specifically, the PEPs are positive at an estimated minimum ethanol selling price of about \$1040/t for the EFB OF scenario and \$1320/t for the EFB FF one; the EFB FF scenario is profitable at a minimum selling price of about \$390/t for C5 syrup. Such values are significantly higher than the prices of ethanol and C5 syrup considered in the analysis (\$760/t for ethanol and \$155/t for C5 syrup: Table 2). Yet, the tendency of the last year has shown that ethanol prices are not expected to rise so dramatically (CEPEA, 2015). As a result, the ethanol price factor discourages the implementation of 2G ethanol single production in a prospective EFB-based biorefinery.

Keeping the scale constant, one possible way to improve the economic efficiency of the 2G ethanol plant would be to integrate the 2G ethanol pathway with biodiesel production and share the investment costs of the common process units (e.g. WWT, CHP) and revenues across the whole integrated plant. Another alternative could be to produce high value added chemicals within the 2G biorefinery. As seen in Table 7, the production cost of C5 syrup (\$350/t) is more than two times higher than its market price (\$155/t), but the production cost of ethanol (\$849/t) is only 12% higher than its market price (\$760/t). This implies that the production of chemicals with high market values, especially based on C5 sugars, could significantly improve the economics of the plant. Furfural, succinic acid, lactic acid, and xylitol are examples of promising bio-based chemicals in the Brazil context (De Jong et al., 2012).

Allocation factors of the intermediate process streams were calculated and are summarised in Table 8. These factors were employed to perform economic based allocation in the LCA. The

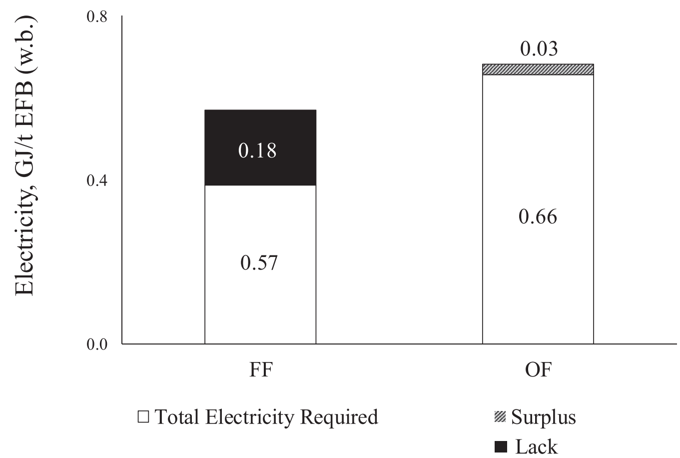

Fig. 3. Electricity produced by the cogeneration part annexed to the biorefinery, the value is divided in two parts: (1) total electricity required to satisfy the 2G plant needs, and (2) surplus electricity produced in each scenario; electricity is given in GJ/t EFB (w.b.).

Table 7
Data and results for economic analysis of EFB FF and EFB OF scenarios.

Scenarios	Units	EFB FF	EFB OF
Ethanol	t/y	24,196	45,094
C5 syrup	t/y	58,841	0
Electricity (purchased/surplus)	GWh/y	−21.14	2.96
Production cost of ethanol	\$/t	849	1038
Production cost of C5 syrup	\$/t	350	0
Production cost of electricity	\$/kWh	–	0.11
TCI[a]	M\$	204.12	226.63
OC[b]	M\$/y	3.86	8.85
FOC[c]	M\$/y	7.94	8.29
MPP[d]	\$/t	−20.38	−18.07
MSP[e]	\$/t	12.00	12.00
PEP[f]	\$/t	−32.38	−30.07

[a] TCI – total capital investment.
[b] OC – operation cost.
[c] FOC – fixed operation cost.
[d] MPP – maximum purchasing price for feedstock (EFB).
[e] MSP – minimum selling price for feedstock (EFB).
[f] PEP – prospective economic performance.

Table 6
Main and intermediate products of the biorefinery using EFB as feedstock.

Scenario	Ethanol	Syrup	Biogas	Surplus Electricity	Steam Demand[b]
	kg/t EFB (w.b.)	kg/t EFB (w.b.)	GJ/t EFB (w.b.)	GJ/t EFB (w.b.)	GJ/t EFB (w.b.)
Feed and Fuel (EFB FF)	58	140	0.25	−0.18[a]	1.97
Only ethanol (EFB OF)	107		1.21	0.03	1.09

[a] This negative value refers to an electricity need from an external source.
[b] Steam demand is the total steam required by the plant.

Table 8
Allocation factors for EFB biorefinery process for EFB FF and EFB OF scenarios.

Process stage	Stream	EFB FF (%)	EFB OF (%)
Harvesting	EFB	97.59	97.59
	FFB	2.41	2.41
Pre-treatment	Liquid frac.	77.08	–
	Solid frac.	22.92	–
Hydrolysis and fermentation	Fermentation beer	100.00	100.00
Distillation and ethanol recovery	Ethanol	100.00	99.27
	Lignin	0.00	0.39
	Filtrate	0.00	0.34
WWT [a]	Biogas	0.00	0.61
	Sludge	0.00	0.53
	Recycled water	100.00	98.86
Cogeneration	Electricity	56.61	73.97
	Heat	43.39	26.03

[a] Waste water treatment.

brief analysis of these results could anticipate the greatest influence of fuel ethanol in the environmental performance of selected scenarios.

4.3. Environmental assessment results

The main results of the LCA for the selected palm EFB-based biorefinery scenarios are illustrated in Figs. 5 and 6, including climate change (A), fossil fuel depletion (B), human toxicity (C), freshwater ecotoxicity (D), and freshwater eutrophication (E) impacts. Fig. 5 shows the overall LCA results of each scenario and the associated RS, and the breakdown of total impacts into those provided by the different services. Fig. 6 depicts the breakdown of the results into the main emission sources. Specifically, LUC shows the part of the CO_2 eq. retrieved from the atmosphere; it has a negative

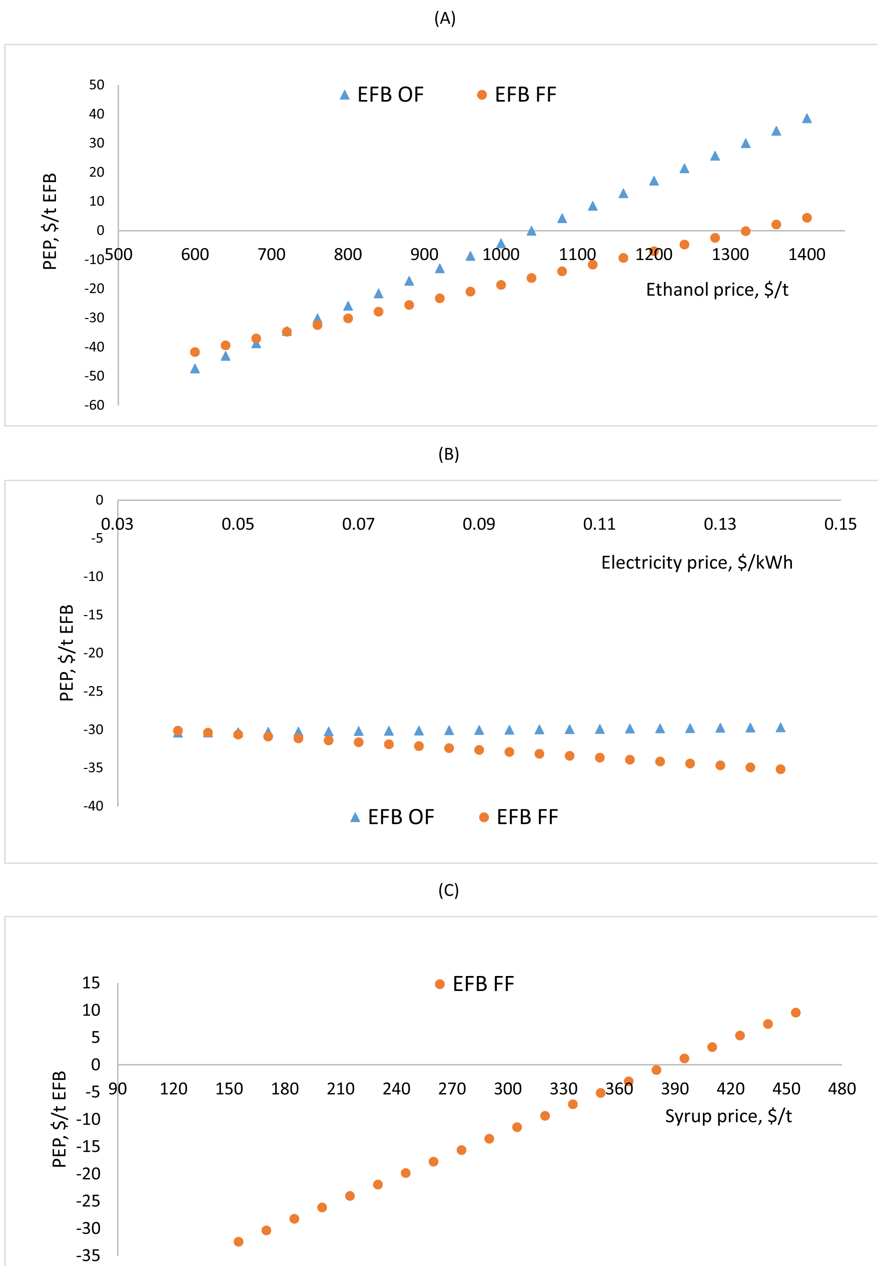

Fig. 4. Sensitivity analysis of prospective economic performance of the two scenarios (EFB FF and EFB OF) for ethanol (A), electricity (B), and C5 syrup (C) prices.

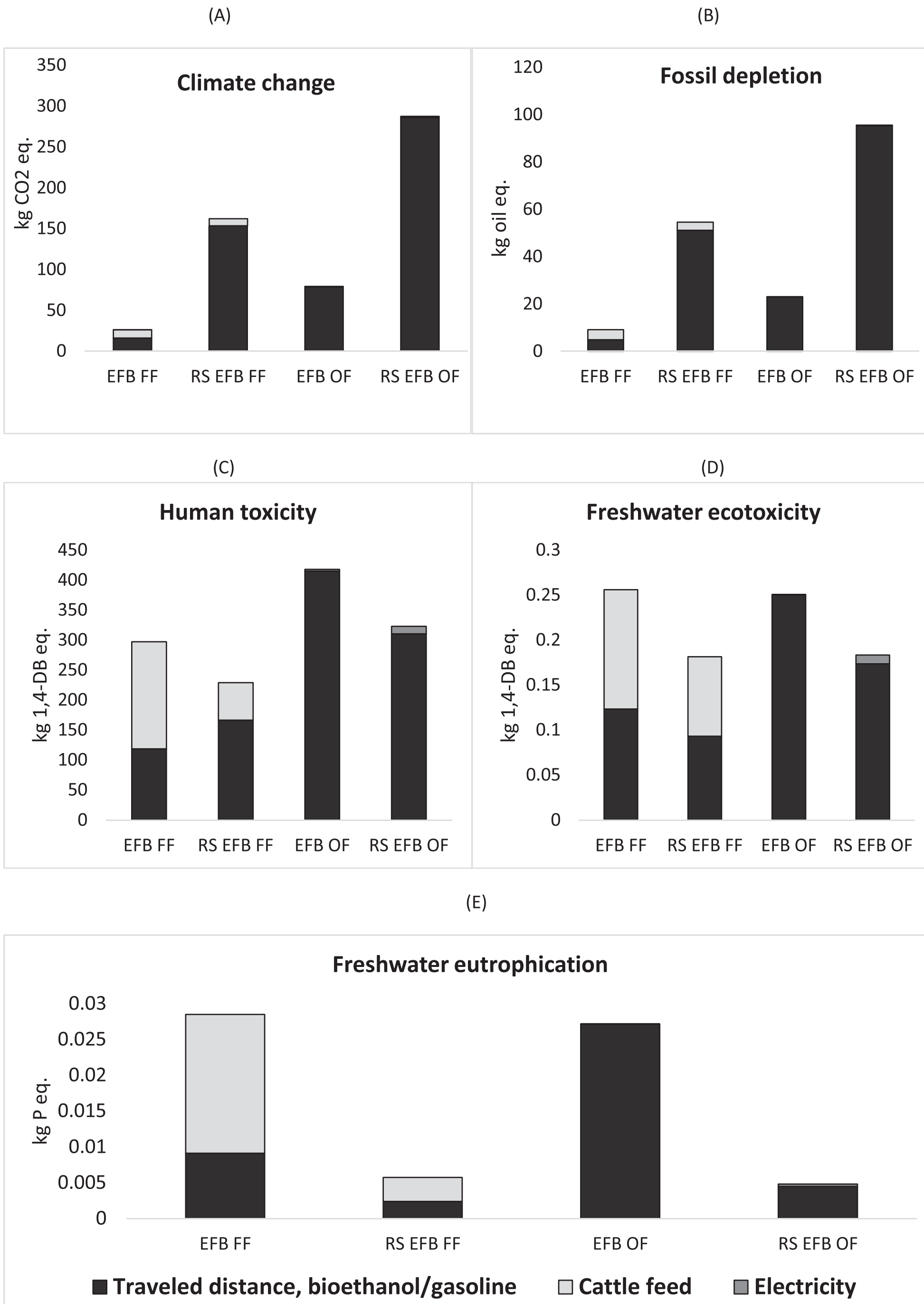

Fig. 5. Results of LCA for EFB FF and EFB OF scenarios and their references systems (RS): for climate change (A), fossil depletion (B), human toxicity (C), freshwater ecotoxicity (D), and freshwater eutrophication (E) impacts; results are presented with a breakdown in impacts of services provided by biorefinery products.

sign and is included only in the climate change impact category; tailpipe represents the exhaust emissions of fuel combustion; the enzyme module corresponds to the emissions caused by enzyme production; the transportation module includes the emissions caused by the transportation of the feedstock to the plant and ethanol from the plant to the gasoline station; the agricultural phase shows the impact caused by the production of EFB; electricity, ethanol, and syrup modules represent the emissions associated with their conversion processes from EFB to the final products excluding the emissions of enzyme production. Notably, the emissions modules are not overlapping. Tables A12-A16 (supplementary material) present the numerical results for Fig. 6. In addition, the LCI tables with all inputs and outputs of the process stages per 1 t of EFB (w.b.) are available in the supplementary material (Table A10 for EFB FF and A11 for EFB OF).

The results of the LCA demonstrate that the biorefinery fossil fuel depletion and climate change impacts are lower than impacts associated with the RSs for the considered biorefinery scenarios. For the climate change absolute impacts, the EFB FF scenario results in 26 kg CO_2 eq./t EFB versus 162 kg CO_2 eq./t EFB in the RS. In turn, EFB OF results in 79 kg CO_2 eq./t of EFB, which is less than half of its RS at 288 kg CO_2 eq./t EFB. The absolute results for the fossil

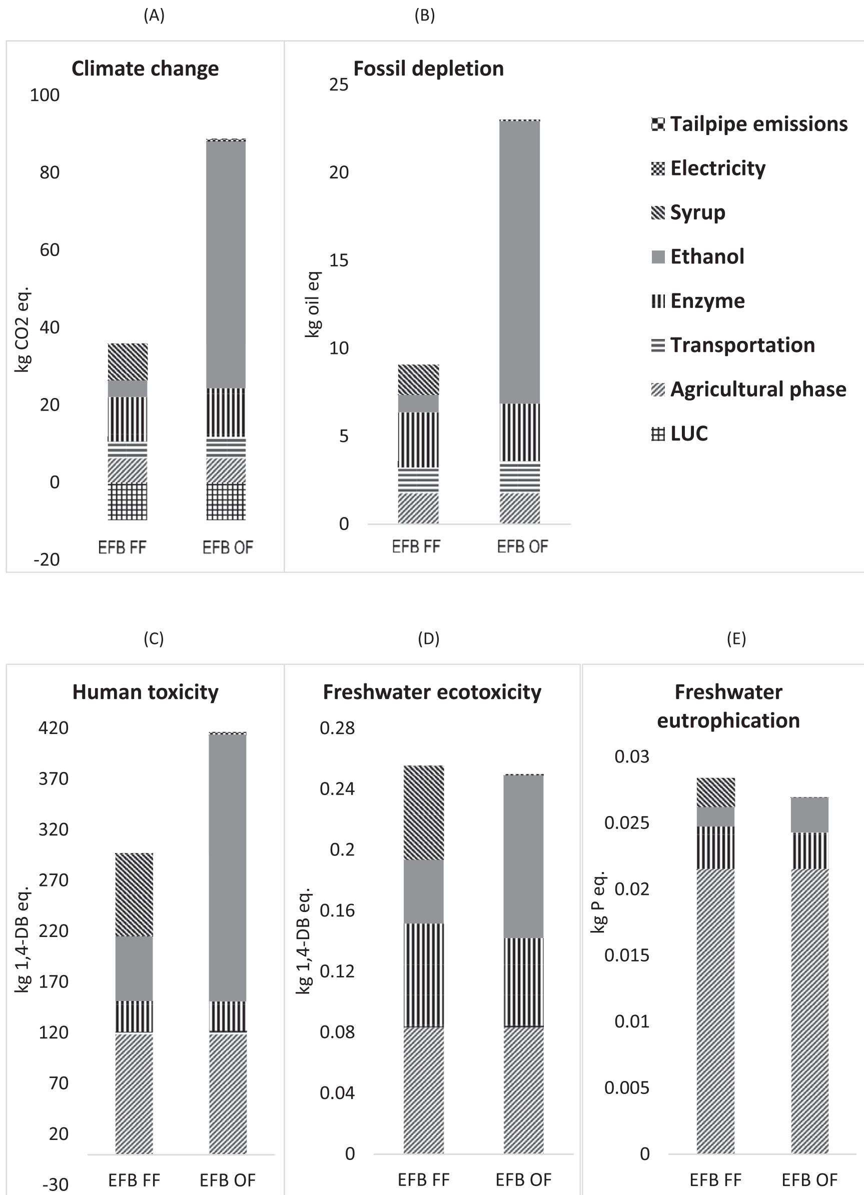

Fig. 6. Breakdown of environmental impacts in emissions sources for climate change (A), fossil depletion (B), human toxicity (C), and freshwater ecotoxicity (D), and freshwater eutrophication (E).

depletion impact of EFB FF and the RS are 9 versus 55 kg oil eq./t EFB; the results for the EFB OF and its RS are 23 versus 96 kg oil eq./t EFB. As can be seen, the absolute results of both are higher for the EFB OF scenario than for the EFB FF. This can be explained by the greatest travelled distance contribution, which is based on the emissions associated with ethanol production being higher in the EFB OF scenario (Fig. 6). The reason for this trend is that the consumption of chemicals (e.g. sulphuric acid, ammonia, lime, caustic) for ethanol production is much higher in the EFB OF scenario (where DA pre-treatment is used) than in the EFB FF scenario (using LHW pre-treatment) (see Table 3, and Tables A10 and A11 in the supplementary material). At the same time, EFB OF provides greater absolute impact reduction in comparison with the RSs than the EFB FF scenario. This means that a larger quantity of emissions (CO_2 eq. and kg oil eq.) could be avoided per 1 t of EFB in the case of the EFB OF plant compared to the EFB FF plant. This can be explained by the higher proximity between the co-products in the EFB FF scenario and their counterparts in its RSs.

The results of the evaluation of the GHG emissions caused by land use change indicate an annual credit of 0.46 t C/(ha y) leading to 93.21 kg CO_2 eq./t FFB. After applying the allocation factor of EFB (2.41%, Table 8), the annual sequestration of CO_2 eq. from the atmosphere per 1 t of EFB is 9.7 kg CO_2 eq. (Fig. 6, Table A12).

The relative results of the LCA indicate the impact reduction percentage brought about by the biorefinery in comparison with the RS. The relative impact reduction is an important factor in the evaluation of the biorefinery scenarios since it shows the potential impact mitigation in case of the replacement of conventional products. For climate change impact, the EFB FF scenario shows a better result than the EFB OF (84% versus 73% impact reduction). The impact of reduced fossil depletion shows a similar trend for EFB FF and EFB OF: 83% versus 76%. These results and the comparison results of absolute impacts between both scenarios, provide evidence that the EFB FF scenario is more favourable than the EFB OF

Table 9
Results of uncertainty analysis.

Impacts category	Probabilities, %	
	RS EFB FF ≥ EFB FF	RS EFB OF ≥ EFB OF
Climate change	100	99.9
Fossil depletion	100	100
Human toxicity	49.6	47.9
Freshwater ecotoxicity	48.6	47.8
Freshwater eutrophication	0	0.6

Note: The results are presented as the probability (%) of the event in which environmental impacts of biorefineries (EFB FF and EFB OF) would not be higher than the environmental impacts in their corresponding references systems.

one, for the relative mitigation of GHG and use of fossil based resources. However, other simulations with a wider range of products would have shown distinct results between scenarios. In general, the results prove that a palm EFB-based biorefinery could provide significant environmental benefits in terms of an impact on climate change and fossil depletion in comparison with conventional processes.

The evaluation of both scenarios in terms of human toxicity, freshwater ecotoxicity, and freshwater eutrophication demonstrates less efficiency in the biorefineries (Fig. 5(C), (D) and (E)) in comparison with the RSs. As a matter of fact, the production of ethanol and C5 syrup requires intensive cultivation of land with a high use of fertilisers, pesticides, and herbicides, among others, in order to produce biomass feedstock (EFB in this study), while, for the RSs, the equivalent amount of car operations can be produced without such land exploitation. The results depicted in Fig. 6 (C, D, and E) illustrate that the agricultural phase of EFB production provides the greatest contribution to the considered impacts, especially to the eutrophication impact. However, it should be noted that the influence of the agricultural phase is vulnerable to uncertainty in the case of the economic allocation of EFB and palm fruits because the EFB economic allocation factor depends on the EFB market prospects that are not yet clear in the industry. The scale effect of massive gasoline production could mitigate the negative effect of petrol emissions on human toxicity, freshwater ecotoxicity, and eutrophication impacts per km of car operation. Through the comparison of the scenarios, of note, the EFB OF biorefinery shows slightly lower results than the EFB FF for freshwater ecotoxicity and eutrophication, but higher results for human toxicity. This can be explained by the larger use of water resources in the EFB FF scenario (see Table 3, and Table A10 and A11 in supplementary material). Still, the EFB FF scenario consumes less toxic chemicals to run the production process than the EFB OF.

Table 9 presents the results of the uncertainty analysis completed via the Monte Carlo simulation for the considered impacts. The results of the uncertainty analysis are presented as a probability (%) of an event where the environmental impact of the biorefinery system would not be higher than the environmental impact in the corresponding RS. The impacts for climate change and fossil depletion are 100% for both scenarios, which means that biorefineries are better than the corresponding RSs in all variations. The impacts for human toxicity and freshwater ecotoxicity range from 47.8% to 49.6% in both scenarios. The probability that the biorefineries would have a lower impact than the RSs in freshwater eutrophication is close to zero. Comparing the results of the uncertainty analysis with the numerical results of the LCA (Fig. 5), the conclusion is that climate change, fossil depletion, and eutrophication impacts are highly correlated, while human toxicity and freshwater ecotoxicity impacts are less relevantly correlated.

5. Conclusions

Two scenarios of the conversion of palm EFB residue into ethanol, heat and power, and cattle feed were evaluated according to techno-economic and LCA principles. Both scenarios show significant benefits in terms of a reduction in climate change (84% for EFB FF and 73% for EFB OF impact reduction) and fossil fuel depletion (83% for EFB FF and 76% for EFB OF) in comparison with relevant reference systems. However, the reduced economic prospects and increased environmental impact levels associated with toxicity and eutrophication lead to big concerns with the implementation of small and medium scale biorefineries. Specifically, the PEP values in terms of $/t of EFB feedstock are $-32.38/t for EFB FF and $-30.07/t for EFB OF. Analysing absolute results for both scenarios, the conclusion is that the 'only fuel' (EFB OF) scenario shows a better economic prospect but worse results for climate change, fossil fuel depletion, and human toxicity impacts than the EFB FF scenario. Such environmental findings are explained by different pre-treatment methods used in the selected scenarios with respect to the considered context. Although the DA pre-treatment is more efficient than the LHW technique, a larger consumption of chemicals in the EFB OF case leads to severe environmental disadvantages. The difference in economic performance is explained by market advantages of fuel ethanol in comparison to cattle feed based on C5 syrup. The investigation of the conversion of EFB into high value-added chemicals could improve the economic and environmental performances of the project.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.07.218.

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